Stiffness and Failure Behavior of Model Hybrid Composites

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ABSTRACT

Many applications are exploring the use of hybrid composites; i.e., polymers reinforced with two different types of fibers, because such systems can have a superior balance of properties and/or a better balance of properties and cost. Unfortunately, the behavior of hybrids is not adequately modeled with current theories. This paper examines the properties of a simple model hybrid made by combining one to four individual tows of glass and carbon into unidirectional samples. To determine the role of the resin, samples were made with and without resin. The experiments on single fibers showed that they behave as expected so failure can be described with Weibull statistics. For tests on individual and hybrid tows, the measured stiffnesses generally fit with predictions from the moduli of the individual fibers using a rule of mixtures model. The failure behavior of tows with no resin is a cumulative process in which the fibers seem to behave independently so the results can be modeled fairly well from knowledge of the fiber mix and the failure behavior of the individual fibers. When resin is present, the failure behavior shifts to catastrophic although samples containing significant glass exhibit some gradual failure before complete fracture. The hybrid samples were found to show a so-called "hybrid effect" in that the strength was higher than would be expected based on simple failure models.

Keywords: Hybrid, failure, fibers, carbon, glass

INTRODUCTION

In recent years, many important applications including off-shore oil recovery, civil infrastructure, and aerospace have considered the use of hybrid composites [1,2]. There are many types of hybrid composites, but one of the most frequently mentioned involves a polymer reinforced with two different types of fibers. The motivation for considering hybrids is that they can offer a superior balance of properties and/or an improved trade-off of properties and cost. The most common hybrid combines carbon fibers for high performance with glass fibers for low cost. To achieve a synergistic effect, however, the fibers must be combined in the proper way. Since this behavior is not adequately modeled

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with simple theories, developers must design the materials based on trial and error tests that are time consuming, expensive, and seldom produce optimum systems. The best known example [3] of an inadequate prediction is the so called "Hybrid Effect." This is the term used to describe behavior where the measured tensile strength in the fiber direction for a unidirectional hybrid is higher than what would be expected from simple models. In addition, recent work has found a number of other areas where improved theories are needed [4-6].

To address this concern, the National Institute of Standards and Technology (NIST) and the University of Houston initiated a collaborative program to understand the behavior of hybrids by characterizing performance and microstructure for a series of model systems. There are many possible types of hybrids based on the fiber mix ratio and the level at which the fibers are mixed. With interply hybrids, each ply contains only one fiber type while intraply systems mix tows of one fiber with tows of another within each ply. Intratow hybrids mix different fibers within each tow. The initial focus of the joint program with Houston is unidirectional, intraply hybrids made by reinforcing epoxy with carbon and glass fibers. Such systems are of particular interest to the oil industry for off-shore drilling platforms [2,5,6].

This paper reports on one aspect of the NIST part in the joint research effort. After characterizing the behavior of the individual components (resin and fibers), the study here examined a series of highly idealized model systems. In a unidirectional, intraply hybrid, the simplest building block is the tow so the work focused on tensile behavior of individual tows and combinations of tows. Both the moduli and strengths were examined.

EXPERIMENTS

The samples utilized carbon fibers (Grafil: 34-700) and glass fibers (PPG: 1062) [7]. In both cases, the tows had no twist and had a standard sizing for epoxy resins. Tests were performed on individual fibers extracted from the tows, on individual tows or groups of tows with no resin added (dry tow tests), and on individual tows or groups of tows with just enough resin added to encase the fibers (impregnated tow tests). When resin was used it was an aromatic amine epoxy composed of EPON 862 (100 parts by mass) cured with EPICURE W (26.4 parts by mass), both from Shell. The impregnation was performed on a Research Tool prepregger using a specially designed take-up fixture that produced flat samples about 25 cm long. The samples were cured in an oven using a cure cycle of 65 °C (150 °F) for 10 h followed by 121 °C (250 °F) for 12 h. A minimum amount of resin was used so that the resin contributed little to the properties of the tows except for facilitating stress transfer among the fibers. Consequently, the resin was not considered in the calculation of stress for the tow tests.

To scan the range of compositions from all glass to all carbon, 5 different sample types were examined: (a) 1 to 3 glass tows, (b) 3 glass tows combined with 1 carbon tow, (c) 1 glass tow combined with 1 carbon tow, (d) 1 glass tow combined with 3 carbon tows, and (e) 1 or more carbon tows. All five types were prepared and tested as impregnated tows while only a, c, and e were tested as dry tow samples.

The tensile tests were conducted on a United Tensile Test Machine (Model FM-10) with a custom built data acquisition system. The individual fibers were tested to determine strength but not modulus using ASTM-D3822. The glass was examined at two different lengths while only one length was tested for carbon. In each case, between 20 and 50 successful tests were performed. To measure the properties of the tows, metal tabs were bonded to each end using American Cyanamid FM-123-2 adhesive. Strain in the tows during the test was determined using a United Laser Extensometer so no direct contact with the sample was needed. The software for the extensometer was modified to work with the data acquisition system. The tow specimens were about 12 cm between the tabs while the gage section was about 8 cm long. For each specimen type, anywhere from 5 to 25 samples were tested. The relative uncertainties in the measurements are ±0.2 % for load, and ±2 % for stress while the standard uncertainty in the strain is ±0.0005. Error bars in figures and ± values in the tables also represent the standard uncertainty.

RESULTS

For the individual fibers, the measured behavior was exactly as expected [8-10]. There was a distribution in strength, and it could be described by a Weibull equation

$$P = 1 - e^{-(\sigma/\sigma_o)^{\beta}} \qquad \textbf{(1)}$$

where P is the probability of failure, σ is the applied stress and the parameters σ_o and β are the average strength and shape factor, respectively. The Weibull parameters determined in the experiments are given in Table I. Although the data are very limited, the trends are consistent with previous studies in that β was essentially the same at both lengths tested for glass while σ_o decreases with increased length.

Table I: Weibull Parameters

Fiber	Length (mm)	σ_o (GPa)	β
Glass	19.6 ± 0.5	3.42 ± 0.02	4.83 ± 0.23
Glass	7.7 ± 0.5	3.91 ± 0.02	4.85 ± 0.15
Carbon	19.6 ± 0.5	5.90 ± 0.05	4.29 ± 0.28

Figure 1 shows typical results for stress-strain curves with all glass or all carbon tows. Curves for both dry tows and impregnated tows are given. As expected, the carbon tows are stronger and stiffer but have a lower extension to failure. The curves show that the addition of resin does not change the initial slopes, and the moduli calculated from the slopes are in good agreement with published values for the fibers. The dry tows fail by a commutative process in which the breaking of individual fibers can be heard as the stress level rises. The stress goes through a maximum and then drops to a very low level. As the strain increases further, the stress remains at a relatively constant value slightly above zero. The simplest explanation is that all the fibers are broken, and the small load corresponds to frictional forces as the fibers slide past one another. These loads are small enough to be ignored in the modeling discussed below.

A very simple model for this behavior assumes that the fibers act individually and each fails according to Weibull statistics [8,9]. If this is true, the total stress in the tow, σ_T, at any given strain, ε, is equal to the product of the fiber modulus, E, the strain, and the fraction of fibers that have not broken at that strain. By using eq. (1) written in terms of strain, the total stress can be written as

$$\sigma_T = E\,\varepsilon\, e^{-(\varepsilon/\varepsilon_o)^{\beta}} \qquad \textbf{(2)}$$

where ε_o is the average strain to failure of the fiber. In theory, all of the parameters in eq. (2) can be obtained from single fiber tests so potentially there are no adjustable parameters. In practice, however, ε_o depends on sample length which is considerably different in the single fiber tests and the tow tests conducted here. Consequently, ε_o was treated as an adjustable parameter. The moduli were not determined in the single fiber tests but can be obtained from the impregnated tow experiments as discussed below.

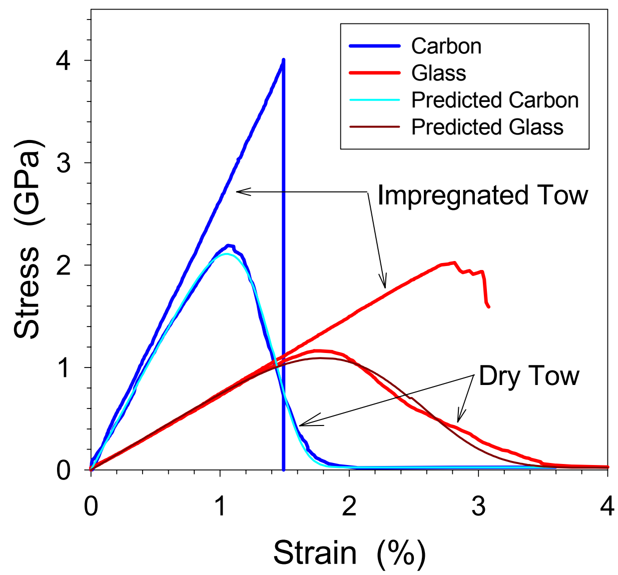

Figure 1: Behavior of individual dry and impregnated tows.

Two different procedures were used to analyze the dry tow data. First, the experimental results were fitted to eq. (2) with both E and ε_o as adjustable parameters. Second, the data were fitted taking E as the value from the impregnated tow tests and varying only ε_o. Both procedures gave virtually identical results. When E was allowed to vary, the fitting process produced values for the moduli that were essentially the same as those determined in the tow tests. Typical examples of best fit curves for glass and carbon tows are shown in Figure 1. The agreement is very good.

Figure 1 also shows the importance of the resin in the mechanical behavior. Unlike the dry tows, the impregnated tows exhibit relatively linear behavior all the way to failure. This makes the test a preferred method for determining fiber modulus. The first line in Table II (Single Impregnated Tow) lists the average moduli for the two fibers obtained from the slope in the stress-strain. This line also lists the average failure strain defined as the strain at maximum stress in the stress-strain curves (Figure 1). For comparison, the second line in Table II (Single Dry Tow) lists the average values of E and ε_o obtained by the fitting process discussed above where both E and ε_o were allowed to vary. As mentioned previously, the moduli obtained from the two tests are virtually identical. What may be more surprising, however, is that the strain to failure values are also very similar despite the fact that the measurements are somewhat different. Because the data are so limited, this agreement may be just a coincidence. Further studies are needed to examine this question.

Table II: Tow Properties

Sample	E_c (GPa)	E_g (GPa)	Failure strain or ε_o	
			Carbon (%)	Glass (%)
Single Impreg. Tow	254 ± 21	73.2 ± 3.6	1.43 ± 0.14	2.94 ± 0.33
Single Dry Tow	251 ± 14	69.6 ± 8.0	1.41 ± 0.08	2.80 ± 0.37
Hybrid Dry Tows (1 carbon - 1 glass)	261 ± 73	57.1 ± 3.4	1.53 ± 0.19	3.28 ± 0.39

It is also clear from Figure 1 that the addition of the resin permits the tows to carry almost twice as much stress. This effect is well known. With no resin present, once a fiber breaks it no longer carries any load. When resin is present and a fiber breaks, the resin transfers the load around the break so parts of the fiber away from the break can still carry significant loads. The resin also changes the failure behavior. Unlike the cumulative failure seen in the dry tows, the impregnated samples fail catastrophically. The carbon tows literally explode with little prior warning, and virtually the entire sample is gone with very few large pieces found after failure. The glass tows, however, generally give a warning prior to complete failure with sounds and slight drops in the stress. Although the ultimate failure is catastrophic, the glass-tow sample generally breaks into 2 pieces which are otherwise largely intact. A number of studies [8-11] have tried to predict the failure behavior of impregnated tows from a knowledge of the constituent properties, but success has been limited so further study in this area is needed.

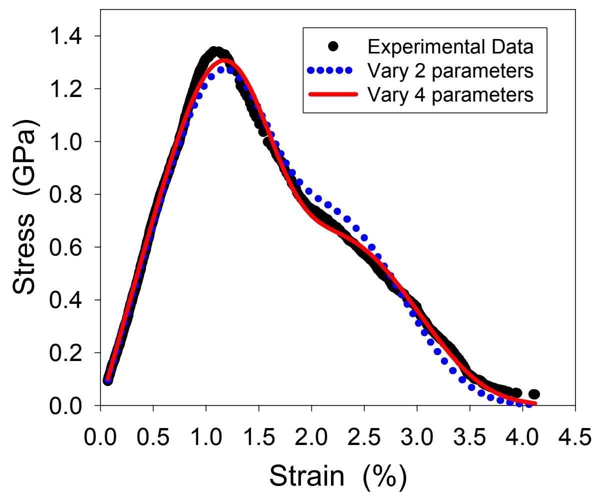

Figure 2: Data for a dry hybrid tows (1 carbon - 1 glass) sample and fits with model.

Figure 2 shows the stress-strain curve for a hybrid sample containing 1 carbon tow and 1 glass tow but no resin. As would be expected, it exhibits a commutative failure like the all glass or all carbon samples. The shape appears to be the combination of 2 peaks which suggests the fibers are behaving independently so a generalized form of eq. (2) might be applicable.

$$\sigma_T = V_c E_c e^{-(\varepsilon/\varepsilon_{oc})^{\beta_c}} + V_g E_g e^{-(\varepsilon/\varepsilon_{og})^{\beta_g}} \qquad \textbf{(3)}$$

where V is the fiber volume fraction while the subscripts c and g indicate quantities for carbon and glass, respectively. As before, the dry tow data for the 1 to 1 hybrid were analyzed by fitting with eq. (3) in two ways: first both moduli and average failure strains were allowed to vary and second, the moduli were fixed using the impregnated tow results. In both cases a reasonable fit was obtained although allowing the moduli to vary produced somewhat better fits (see lines in Figure 2 for example). The third line in Table II (Hybrid Dry Tows) lists the average values for all samples obtained by allowing all 4 parameters in Eq. (3) to vary in the fitting process.

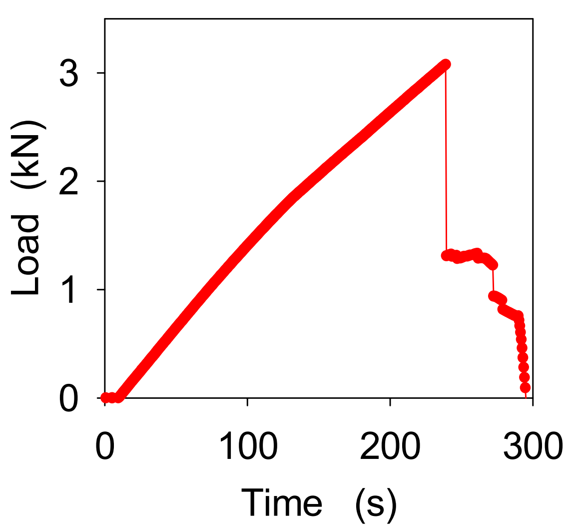

Figure 3: Stress-time curve for an impregnated hybrid tows (1 carbon - 1 glass) sample.

The main effect of allowing the moduli to vary in the fitting process was that the modulus obtained for the glass was somewhat lower while the corresponding strain to failure was higher. One factor that may contribute to this difference is that it is difficult to keep all fibers in both tows equally aligned and stretched in the final sample. In any case, this simple model provides, at least, a good first order fit of the data.

The stress-time behavior of the impregnated

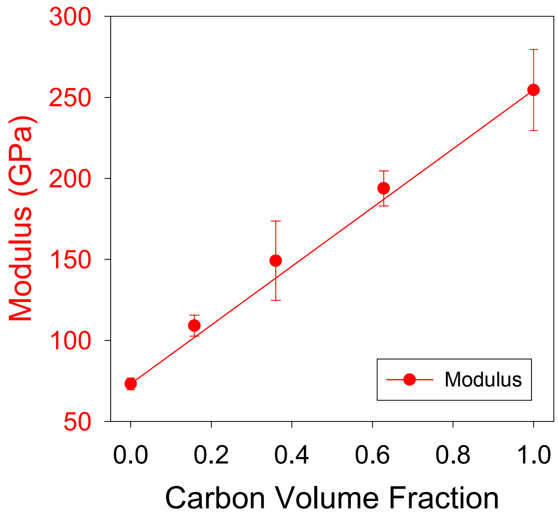

Figure 4: Hybrid modulus data and model. Bars indicate standard uncertainty in the data.

hybrid tows is illustrated in Figure 3 which shows data for a 1 to 1 hybrid sample. In these samples, the behavior prior to failure is nearly linear so there is a sizable linear region that can be used to determine a modulus. Figure 4 shows a plot of the average moduli obtained from the linear regions in the stress-time plots as a function of carbon fiber volume fraction. As expected, the results can be described with a simple rule of mixtures model (straight line in Figure 4).

For the impregnated hybrid tows, failure was defined as the point where the stress drops from a maximum (Figure 3). The average failure strengths are shown in Figure 5 as a function of carbon fiber volume fraction. It is interesting to note that the addition a small amount of carbon fiber decreases the failure strength. To model these results it is useful to observe the sample before and after the failure point (Figure 6). The initial drop (Figure 3), which defines the failure point, occurs when the carbon tow(s) break. The glass tows continue to support some load, but then fail after a slight increase in strain. The failure of the carbon tow(s) clearly damages the glass tow(s) since the ultimate strain at failure for these tows is much less than that for samples containing only glass. This general picture of failure is reasonable since the carbon fibers have a much lower extension to failure than the glass fibers and therefore should fail first.

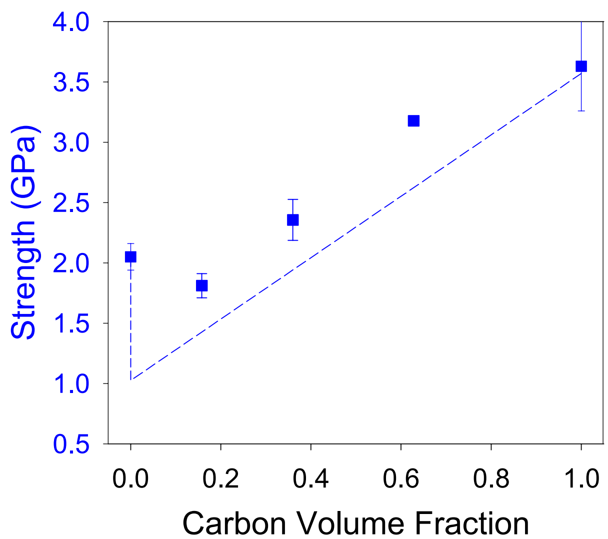

Figure 5: Hybrid failure data and model. Bars indicate standard uncertainty in the data.

Based on this idea, a very simple model for hybrid failure behavior can be examined. This model assumes that the sample fails when the strain reaches the failure strain of a carbon tow. The prediction of this theory are shown in Figure 5 as a dashed line. Just as observed in the experimental results, the model predicts that the addition of a small amount of carbon to glass will reduce the strength. The reason is that the strain to failure is reduced from that of glass in the all class sample (about 3 %) to that of carbon in the hybrid (about 1.5 %). Although the carbon fibers are stiffer and carry more load at a given strain, this effect is overwhelmed by the lower strain at failure when only a small amount of carbon is present. Thus, the strength decreases. The dashed line in Figure 5,

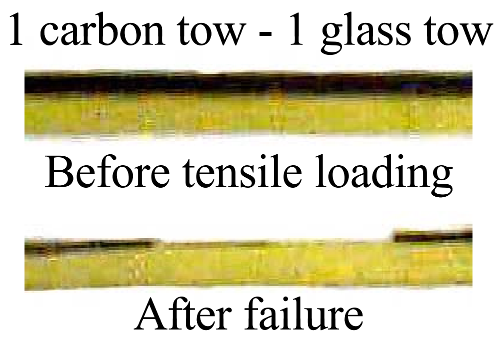

Figure 6: Hybrid sample before and after initial failure.

however, is clearly an oversimplification. As the amount of carbon in the hybrid is decreased, a point will surely be reached where failure of the carbon no longer constitute failure of the hybrid. Consequently, the transition of all glass to hybrid will be more gradual than that indicated by the dashed line in Figure 5.

The most striking feature of the theory, however, is that, the experimentally measured average strength is significantly above the predictions for all three types of hybrids. Consequently, the results show that the samples exhibit the well known "Hybrid Effect." When the hybrid effect is present, it generally means that the carbon tow(s) are stretched to a higher stain before failure when the glass tow(s) is present than when there is only a carbon tow. One possible explanation is residual compression strains in the carbon fiber as a result of differences in thermal expansion coefficients in the glass and carbon fibers. Calculations indicate, however, that this effect is very small and cannot explain the observed results. Moreover, the fact that the samples are straight indicates that the thermal expansion effects are small. Significant differences in thermal expansion would cause the samples to curve.

Although there does not seem to be any simple explanation for these results, it is interesting to note that the failure behavior of the carbon tow changes slightly when a glass tow is present. Large sections of the carbon tow often remain in tact suggesting a somewhat more stable or controlled failure process. In any case, more work is needed to provide a valid micromechanics explanation for these results.

CONCLUSIONS

An experimental study was conducted on a model glass-carbon hybrid composite. The results show that the fibers, themselves, behave as expected with a distribution in strength consistent with Weibull statistics. For tests on individual and hybrid tows, the measured stiffnesses generally fit with literature values and predictions using a simple rule of mixtures model. The failure behavior of the tows with no resin is a cumulative process in which the fibers seem to behave independently. In most cases, the behavior can be modeled fairly well using only knowledge of the fiber mix and failure behavior of the individual fibers. When resin is present, the failure behavior shifts to catastrophic fracture although samples containing any glass may exhibit a slightly more controlled fracture. The hybrid samples were found to show a so called "hybrid effect" in that their strength was higher that would be expected based on simple models for behavior.

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